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SUMMARY OF ACOUSTIC AND MECHANICAL CHARACTERIZATION OF COMPOSITE SONAR DOME MATERIALS

J.A. Hiltz – J.P. Szabo – A.J. Russell

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ABSTRACT

This report summarizes research carried out under a DMCS 3 (DMSS 7) tasking entitled "Comparison of the Acoustic, Self Noise, and Mechanical Properties of Composite and Stainless Steel Sonar Dome Materials". It incorporates results from several contracted research programs and DREA Technical Memoranda and is meant to provide a concise record of the tasked research. Static (tensile and compression tests), fatigue and impact testing were used to characterize the mechanical properties of high strength polyethylene (Spectra) and glass fibre composites. Insertion loss measurements were used to characterize the acoustic performance of the composites. The effect of impact damage and angle of incidence of sound on the performance of the composites were also measured. The results show that Spectra fibre composites have superior acoustic properties compared to glass fibre composites and the double walled stainless steel presently used in the C5 sonar dome. However, the mechanical properties of the Spectra composites were inferior to the glass composites.

Résumé

Le présent rapport résume la recherche, effectuée en vertu d'une attribution des tâches de niveau DSCN 3 (DSN 7), portant sur la comparaison des propriétés acoustiques, mécaniques et de bruit propre des matériaux de dôme sonar en composites et en acier inoxydable. Il comprend des résultats provenant de plusieurs programmes de recherche réalisés sous contrat et de documents techniques du CRDA et servira de document concis sur la recherche associée à cette attribution. On a effectué des essais statiques (de traction et de compression), des essais de fatigue et des essais de résistance au choc pour déterminer les propriétés mécaniques de composites à haute résistance faits de polyéthylène (Spectra) et de fibres de verre. On a caractérisé la performance acoustique des composites à l'aide de mesures de perte d'insertion. On a aussi mesuré l'incidence des dommages dus au choc et de l'angle d'incidence de l'onde acoustique sur la performance des composites. Les résultats révèlent que les composites en fibres Spectra possèdent des propriétés acoustiques supérieures à celles des composites en fibres de verre et à celles de l'acier inoxydable à double paroi qui est présentement utilisé dans les dômes sonar C5. Les propriétés mécaniques des composites en Spectra sont toutefois inférieures à celles des composites en fibres de verre.

DREA TM 1999-120

Summary of the Acoustic and Mechanical Characterization of Composite Sonar Dome Materials

John A. Hiltz, Jeffrey P. Szabo and Alan J. Russell

EXECUTIVE SUMMARY

Introduction

This report summarizes research carried out under a DMCS 3 (DMSS 7) tasking entitled "Comparison of the Acoustic, Self Noise, and Mechanical Properties of Composite and Stainless Steel Sonar Dome Materials". The work started in 1994 as the result of DMSS 7 interest in finding materials that would reduce life cycle costs of the double walled stainless steel C5 sonar dome. It incorporates results from contracted research and DREA Technical Memoranda and is meant to provide a concise record of the tasked research. Static (tensile and compression tests), fatigue and impact testing were used to characterize the mechanical properties of high strength polyethylene (Spectra) and glass fibre composites. Insertion loss measurements were used to characterize the acoustic performance of the composites. The effect of impact damage and angle of incidence of sound on the performance of the composites were also measured.

Principal Results

Spectra fibre composites have superior acoustic properties to glass and carbon fibre composites and the double walled stainless steel material now used for the C5 sonar dome. The improvement in acoustic properties increases with frequency up to 100kHz. However, the mechanical properties of Spectra fibre composites are inferior to glass composites. Spectra fibre composites hysteretic heating under cycling loading, creep under sustained mean loads, and have poor properties in compression. Some of these drawbacks might be addressed by increasing the thickness of a spectra fibre composite dome, but this would increase costs and decrease acoustic performance.

Significance of the Results

If higher frequency capabilities for sonar domes are required, Spectra fibre composites offer advantages as dome materials. Calculations indicate that the detection range of a 40 kHz active sonar system incorporating a Spectra fibre composite dome would be eight times farther than a system with a double walled stainless steel dome.

However, glass composites were as much as 50% stiffer in tension and more than four times stronger when loaded in compression than Spectra fibre composites. The spectra composites also exhibited hysteretic heating at moderately low testing frequencies and

large permanent deformations prior to failure in fatigue testing. Use of spectra fibre composite in domes will require careful design to ensure that the dome has the requisite mechanical properties for the in-service conditions.

Future Plans

Noise arising from the material used to construct a sonar dome may be a more significant factor in the performance of a dome than insertion loss. The self noise of the stainless steel dome and candidate composite dome materials should be evaluated.

Composites with decreased density and good mechanical properties should be evaluated. Possible approaches are glass reinforced composites with decreased glass loading or the use of hollow glass reinforcing fibres.

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Introduction

Fibre reinforced plastics (FRP) have a number of properties that make them attractive materials for Defence applications. These properties include high strength to weight ratios, corrosion resistance, radar transparency and good ballistic properties. From the Naval perspective, potential applications for FRPs include masts and superstructures where reduction in topside weight, radar transparency, and corrosion resistance are important.

Another potential application of composites is in the fabrication of sonar domes. The purpose of this structure is twofold: to protect the sonar transducer and electronics from damage due to impacts, and to provide a hydrodynamic surface to minimize flow induced noise associated with the sonar equipment. Protection of the sonar comes with a cost in performance. The dome material attenuates and distorts (change the frequency of) sound passing through it. Further, self noise arising from structurally induced vibrations in the dome and hydrodynamic noise from flow over the dome reduce sonar performance.

There is interest in finding a more durable and less costly, in terms of life cycle cost, dome material. Substitution of a FRP for the double-walled stainless steel material currently used in the C5 sonar dome would require that the composite had the required mechanical properties to protect the sonar, performed at least as well acoustically, and resulted in reduced life cycle costs. Ideally, a composite would lead to improved performance by, for instance, reducing attenuation and distortion of the sonar signal and self noise of the dome.

The results of an evaluation of the acoustic and mechanical properties of high strength polyethylene and glass fibre composites are summarized in this report. The report also contains a complete record of the resins, reinforcing fibres and fabrics, lay-ups, and cures used to fabricate the composite panels.

Background

To help identify a suitable candidate fibre a literature survey was conducted for DREA in 1992 [1]. The literature review focused on higher strength fibres, compared to S-glass. The review indicated that high strength polyethylene (HSPE) fibres had properties, such as specific strength and tensile modulus, that were superior to Kevlar 49 and S2 Fibreglass. In addition, the review noted that HSPE fibres were resistant to moisture absorption, and that HSPE composites exhibited excellent ballistic properties and impact resistance. These properties suggested that HSPE composites might be considered for applications such as sonar domes.

The review also highlighted some shortcomings of HSPE fibres and composites. Surface modification of HSPE fibres was required to improve adhesion of the resin and produce composites with acceptable properties. Also the properties of HSPE composites were inferior to those predicted from single HSPE fibre properties. In addition, the interlaminar shear, flexural, creep and compressive properties of HSPE composites reported in the literature were inferior to S2 fibreglass and Kevlar 49 composites.

The results of tensile and flexural testing of HSPE fabric laminates compared favorably with those found in the literature, although the flexural and tensile stiffness for the composites were lower than reported in the literature. Testing also indicated that the modulus values of the laminates were thickness dependent, with thinner laminates having higher modulus values.

The literature review and preliminary mechanical testing were followed by a study of the effect of environmental exposure on the flexural properties of HSPE composites [2]. HSPE composites incorporating either a plain weave or 8 harness satin weave HSPE fabric reinforcement were exposed to salt water, ultraviolet radiation and moisture condensation and warm salt fog mist. The properties of the plain weave composite degraded when exposed to all three environments while 8 harness weave composite was far less affected by the environmental exposure.

In June 1993, DMCS 3-3-6 [3] outlined in-service problems with the C5 Sonar Dome, including lifecycle costs of the stainless steel dome and sonar performance. The brief recommended that composites be tested as candidate materials for dome manufacture.

A meeting was held at NDHQ in November 1993 where DMCS 3 (now DMSS 7) and DREA outlined a plan of action directed at the development of a composite sonar dome [4]. The plan included the purchase of glass and high strength polyethylene (HSPE) composite tests panels, acoustic and mechanical testing of the panels, and the raising of a Research and Development minor development project request with DRDM.

In July 1994 a tasking entitled "Comparison of the Acoustic, Self Noise, and Mechanical Properties of Composite and Stainless Steel Sonar Dome Materials" was accepted by Director Resource Management Program Control [5].

Rational for Selection of Reinforcing Fibres and Resins

The composites evaluated were HSPE/epoxy, E-glass/epoxy, HSPE/cyanate ester and E-glass/cyanate ester. Two fabric weaves, 8 Harness satin weave and 4 Harness satin weave, were selected for the reinforcing fibres.

The HSPE fibre reinforcement was chosen on the basis of its low density (<1.0 g/cm3) and high tensile strength. Low density is important for sonar window materials because the insertion loss in the window depends on how closely its acoustic impedance, the product of density and speed of sound in the material, matches that of water.

E-glass was selected because its cost and widespread use in composites.

Different reinforcing fabric weaves were tested to determine if the weave had a significant affect on either the mechanical or acoustic properties of the composites. The satin weave fabrics were selected because of their drapability, which facilitates preparation of composites with complex shapes.

The composite prepreg manufacturer recommended the cyanate ester resin. Cyanate ester resins are noted for their excellent electrical properties, resistance to moisture absorption, and good mechanical properties.

The epoxy was selected because of cost and its widespread use in composites.

High Strength Polyethylene Fibre

High strength polyethylene fibres were first marketed in the 1980s by DSM Resins (Dyneema, 1984), Mitsui (Tekmilon, 1984) and Allied Signal (Spectra, 1985). Commercialization resulted from developments in the processing of high molecular weight polyethylene (HMWPE) to form highly oriented molecular chains in the fibres. Orientation is achieved by spinning HMWPE from solution or melt followed by drawing. Manufacturer's literature indicated that the high degree of orientation of molecular chains resulted in fibres with high tensile strength, stiffness, and energy absorption capability and because these fibres were polyethylene, they also had low specific gravity and excellent electrical properties.

Experimental

Materials

Three sets of composite panels were investigated.

The first set of panels included four high strength polyethylene (Spectra) fibre composites and two glass fibre composites.

The prepregs used to fabricate the composite panels were made by Bryte Technologies Incorporated, Milpitas, California. Three fabrics were used to make prepregs. They were Spectra 985PT, an eight harness satin weave fabric woven from 1000 Series plasma treated Spectra fibre; Spectra 988PT, a four harness satin weave fabric woven from 1000 series plasma treated Spectra fibre; and 7781Fg, an eight harness satin weave fabric

woven from E-glass. Each of the reinforcing fabrics was impregnated with either a cyanate ester (BTCy-3) or an epoxy resin (BT250E).

The composite panels were made by Advanced Composites Technology, Sparks, Nevada. The Spectra composite panels incorporated 28 plies of the prepregs (0°, 90°) and the glass composites 36 plies (0°, 90°). Fabrication involved vacuum bagging the assembled prepreg plies and applying a vacuum (25 inches Hg minimum) to consolidate the plies and remove excess resin. The composites were then cured in an autoclave under pressure (0.35 MPa). The cure cycle for the cyanate ester resin composites involved heating from room temperature to 120°C at a rate of 2°C/min, holding at 120°C ± 4°C for 5 hours, and then cooling at 5°C/min to below 70°C and removing the vacuum. The cure cycle for the epoxy resin was the same except that the hold time at 120°C was reduced to 2 hours.

The dimensions of the HSPE composites were 1005 mm x 1005 mm x 10 mm and the glass composites 1020 mm x 1080 mm x 10 mm.

The make up and thickness of the E-glass/epoxy, E-glass/cyanate ester, Spectra/epoxy and Spectra/cyanate ester laminates are shown in Table 1.

Table 1

The fibre, matrix, fibre weave, number of fabric plies, and lay-up orientation of fabric plies used to prepare the six composites. The thickness of the cured composites panels are also listed.

Laminate ID	7781Fg/ BT250E	7781Fg/ BTCy-3	988PT/ BT250E	985PT/ BT250E	988PT/ BTCy-3	985PT/ BTCy-3
Fibre	E-Glass	E-Glass	Spectra	Spectra	Spectra	Spectra
Matrix	Epoxy	Cyanate-Ester	Epoxy	Epoxy	Cyanate-Ester	Cyanate-Ester
Weave	8 harness satin	8 harness satin	4 harness satin	8 harness satin	4 harness satin	8 harness satin
# of Plies	36	36	28	28	28	28
Lay-up	[0/90]	[0/90]	[0/90]	[0/90]	[0/90]	[0/90]
Thickness (mm)	8.3 - 9.2	9.2 - 9.6	9.4 - 9.7	9.6 - 9.8	9.6 - 9.9	9.3 - 9.6

The second set of E-glass/epoxy and Spectra/epoxy composites was 10 mm, 20 mm, and 30 mm thick. The composites were fabricated at Defence Research Establishment

Atlantic, Dockyard Laboratory Pacific from prepregs made by Bryte Technologies Incorporated, Milpitas, California. The prepregs were made from either Spectra 985 or E-glass 7781Fg eight harness satin weave fabric impregnated with BT 250E-1 epoxy resin.

The 10 mm, 20 mm, and 30 mm E-glass/epoxy panels incorporated 40, 80, and 120 prepreg plies (0°/90°) respectively with the exception of one of the 10 mm panels. Every second ply in this panel was orientated at ± 45° rather than 0°/90°. The lay-up stacks were flipped up to down at mid-plane in the panels to avoid imbalances caused by the satin weave fabrics. The 10 mm, 20 mm, and 30 mm Spectra fibre/epoxy panels incorporated 28, 54, and 76 prepreg plies respectively. The cure of the 10 mm panels was the same as described above for the panels made at Advanced Composites Technology except that the autoclave pressure was 0.5 MPa. The cure for the thicker samples was modified to prevent an exothermic overshoot. These panels were heated at a rate of 2°C/min to between 105°C and 110°C and held for 15 minutes before ramping the temperature at 1°C/min to 120°C.

The make-up of 10 mm, 20 mm, and 30 mm glass/epoxy and Spectra/epoxy composites are shown in Table 2.

Table 2
The fibre, matrix, fibre weave, number of fabric plies, and lay-up orientation of fabric plies used to prepare the 10 mm, 20 mm, and 30 mm composites.

Laminate ID	7781Fg/ BT250E-1	7781Fg/ BT250-1	7781Fg/ BT250-1	985PT/ BT250-1	988PT/ BT250-1	988PT/ BT250-1
Fibre	E-Glass	E-Glass	E-glass	Spectra	Spectra	Spectra
Matrix	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy
Weave	8 harness satin	8 harness satin	8 harness satin	8 harness satin	8 harness satin	8 harness satin
# of Plies	40	80	120	28	54	76
Lay-up	[0/90] & [0/90/±45]	[0/90]	[0/90]	[0/90]	[0/90]	[0/90]
Thickness (mm)	10	20	30	10	20	30

The third set of panels was prepared by coating 10 mm E-glass/epoxy panels with elastomeric coatings. The fabrication of the 10 mm composite panels is described in the preceding paragraph.

The piece of double walled stainless steel sonar dome (914 mm x 914 mm x 60 mm) was cut from a C5 sonar dome removed from service. A 20 gauge stainless steel plate (1219 mm x 1168 mm x 0.92 mm thick) was used as a calibration panel for the insertion loss testing.

Results and Discussion

Mechanical Testing

The mechanical properties [6-8] of the Spectra composites were very different from that of the two E-glass composites. This difference was quite fundamental in nature and made it necessary to adopt different testing and data reduction procedures for the Spectra composites to fully characterize their mechanical behaviour.

Static Tests

Static testing was carried out on the composites shown in Table 1. In addition to four point bend tests, which were run to provide a comparison of the stress-strain behaviour with loading in the fibre directions, off-axis properties and interlaminar shear strengths were also measured.

Large differences in the magnitude of the tensile and compressive surface strains measured in the Spectra flexure tests, and the resulting shift in the position of the neutral axis, made the calculation of the surface stresses quite difficult and to some extent less certain. For this reason, separate tension and compression tests were carried out on the Spectra laminates in order to eliminate any doubt about the validity of the data reduction scheme. Figures 1 and 2 show representative stress strain plots for the glass/cyanate ester and one of the Spectra/cyanate ester materials. Although the compression half of the

stress-strain curve is not shown for the glass/cyanate ester, both of the glass fibre composites had equal tension and compression modulii and both failed in tension. Table 3 summarizes some of the test data where a direct comparison of the glass and Spectra materials was possible.

The 8-harness satin weave E-glass fabric composites were as much as 50% stiffer than the 8-harness satin weave Spectra fabric composites in tension and more than four times stronger when loaded in compression. In addition, the glass reinforcement provided more than twice as much in-plane shear stiffness and significantly higher interlaminar shear strengths.

Table 3
Moduli, off axis moduli, and interlaminar shear strengths of Spectra and glass fibre composites.

Laminate ID	7781Fg/ BT250E	7781Fg/ BTCY-3	988PT/ BT250E	985PT/ BT250E	988PT/ BTCY-3	985PT/ BTCY-3
Fibre	E-Glass	E-Glass	Spectra	Spectra	Spectra	Spectra
Matrix	Epoxy	Cyanate-Ester	Epoxy	Epoxy	Cyanate-Ester	Cyanate-Ester
Weave	8 harness satin	8 harness satin	4 harness satin	8 harness satin	4 harness satin	8 harness satin
Tensile Modulus (GPa)	22.0	21.9	10.2-13.1*	14.0-19.9*	7.4-7.8*	14.2-20.2*
Off axis (± 45) modulus (GPa)	11.4	13.7	4.5	4.6	6.3	6.1
Interlaminar Shear Strength (MPa)	56.0	54.6	17.4	20.9	14.9	19.4

* values measured at "slow" and "fast" strain rates

The mechanical properties of the cyanate ester and epoxy resin composites were similar. The higher modulus of the cyanate ester translated into a modest improvement in in-plane shear stiffness and a small increase in compression strength particularly in the case of the 4 harness Spectra fabric. On the other hand, the higher strain to failure of the epoxy matrix produced a higher interlaminar shear strength than the cyanate ester as well as a higher tensile modulus in the 4-harness Spectra fabric. For both matrix materials, the 985

Spectra fabric (8-harness) provided greater stiffness than the 988 fabric (4 harness) under all loading conditions but especially in tension where the difference was almost two-fold.

Fatigue Behaviour

The response to cyclic loading was similar to the behaviour under static loads in as far as the glass composites behaved in a predominantly linear elastic manner and failed in tension, while the Spectra fibre composites exhibited considerable hysteresis prior to failing in compression. Fatigue tests carried out in four point bending under constant load amplitude showed that there was no significant difference in the fatigue lives of the two glass fibre composites. The effect of R-ratio on the fatigue life of the glass/epoxy system are shown in Figure 3. R-ratio is the ratio of the minimum to the maximum stress applied to the test coupon. For instance, an R-ratio of 0.1 indicates that the minimum stress is a tenth of the maximum stress. Testing also revealed that there was no significant difference between sine wave and square wave loading.

Fatigue testing of the Spectra fibre laminates, which was also carried out in four point bending under constant load amplitude, had to be limited to quite low frequencies in order to prevent excessive hysteretic heating and premature failure. This was especially true at the beginning of each test when the hysteresis was at its maximum as shown in Figure 4 for an R = -1 Spectra/epoxy test. This graph also shows that as the fatigue tests progressed the difference between the tensile and compression strains also decreased markedly, shifting the position of the neutral axis back closer to the mid-plane of the test specimens. No attempt was made to take these changes in moduli into account when calculating the fatigue stresses. Hence, the actual tensile stresses were higher than reported while the actual compressive stresses were lower with the magnitude of both errors decreasing as the tests progressed.

The Spectra fatigue results under reversed bending are summarized in Figure 5. The eight harness satin weave laminates outlasted the four harness satin weave laminates while the cyanate ester matrix out-performed the epoxy matrix.

Fatigue testing of the Spectra fibre composites was also carried out at an R-ratio of 0.1. Some of the test specimens did eventually fail in compression during these tests but it was not clear whether failure was driven by the cyclic load amplitude or by creep due to the sustained mean load. Figure 6 indicates that while the displacement amplitude required to maintain a constant load amplitude gradually decreased, the average displacement increased steadily. When failure did occur it was always preceded by such large permanent deformations that it is unlikely that these kinds of loading conditions could be sustained in a real structure. Although relatively few R = 0.1 tests were run to failure, those that did fail required similar combinations of bending moment and number of cycles as encountered in the R = −1 tests and the ranking of the four Spectra materials was the same.

Impact Testing

Drop weight impact tests were carried out on flat test panels placed on top of a circular support centered directly below an instrumented tup having a curved but relatively flat impacting surface. Initial tests were carried out on 300 mm square panels cut from the same laminates that were used for the static and fatigue tests. The glass fibre laminates were impacted several times at progressively higher energies until failure occurred. Each of the Spectra panels was impacted twice at two different impact energies. None of these tests produced delaminations; the glass fibre laminates failing in tension on the back surface and the Spectra fibre laminates undergoing local plastic deformation. There was very little difference observed between the responses of the two fibreglass materials or between the four different Spectra laminates. In order to determine the conditions necessary for producing delamination, additional 8-harness satin weave epoxy panels were manufactured and tested. The panel thicknesses and the impact conditions that resulted in their failure are shown in Table 4.

Table 4
Summary of impact results for glass/epoxy and Spectra/epoxy composites.

Material	Panel Thickness (mm)	Impactor Mass (kg)	Impact Velocity (m/s)	Impact Energy (kJ)	Peak Force (kN)	Transverse Shear Stress (MPa)	Location and mode of Failure
Glass/Ep	10	21.3	6.2	0.42	61.0	-	back surface tension
Glass/Ep*	10	21.1	6.2	0.41	60.5	48.1	mid-plane delam
Glass/Ep	20	293	2.8	1.15	183	72.8	mid-plane delam
Glass/Ep	30	293	3.2	1.58	332	88.1	mid-plane delam
Spectra/Ep	10	21.1	5.4	0.31	41	32.6	mid-plane delam/pl
Spectra/Ep	20	293	2.4	0.86	89	35.4	mid-plane delam/pl
Spectra/Ep	30	293	2.8	1.18	127	33.7	mid-plane delam/pl

* Quasi-isotropic lay-up. All other panels were [0/90] pl = plastic deformation

As before, the glass fibre composites were impacted at progressively higher energies until failure occurred while the Spectra composites were impacted only once. The transverse shear stresses shown in Table 4 were calculated from the peak force exerted by the tup at the location corresponding to the periphery of the tup contact region. This parameter has been shown to be a reasonably good predictor of delamination under most conditions. The force – strain plots for the 20 mm thick panels shown in Figures 7 and 8 indicate that delamination onset was marked by a sudden drop in load for the glass/epoxy composites but not for the Spectra/epoxy composites. Consequently, further testing would be required to set a lower limit on the transverse shear stress necessary to produce delaminations in the Spectra/epoxy composites. For glass/epoxy composites, the transverse shear stress at delamination onset in the quasi-isotropic lay-up was significantly lower than in the [0/90] lay-up.

A final set of impact tests was carried out in order to evaluate the possible beneficial effects of elastomeric coatings in preventing impact damage. Three different elastomers were applied to one surface of 10 mm thick glass/epoxy panels which were then impacted with sufficient energy to damage an unprotected panel. The panels were impacted a total of five times using the same impact conditions in order to quantify any degradation in the ability of the elastomers to protect the panels and to allow sound transmission. Table 5 summarizes the reductions in peak force and peak panel strain provided by the elastomers

on the first and second impacts. While all of these reductions were sufficient to prevent damage to the back surface of the panels, the overall level of protection was quite modest. The ranking of the elastomers in terms of peak force reduction was the reverse of the more pertinent ranking in terms of strain. This apparent discrepancy can be explained by the different stiffnesses of the elastomers; the polyurethane increasing the panel stiffness the most followed by the Isodamp C-1002.

Table 5

Reductions in peak force and peak strain for impacted composite panels coated with a polyurethane, Isodamp C-1002 and natural rubber.

	Impact #	Polyurethane	Isodamp C-1002	Natural Rubber
Reduction in Peak Force (%)	First	16.2	20.2	27.7
	Repeat	13.4	18.5	26.2
Reduction in Peak Strain (%)	First	26.8	25.6	23.5
	Repeat	25.4	26.6	19.3

Acoustic Properties

The acoustic data summarized in this report is taken from references 9 through 12.

Insertion Loss

Spectra and Glass Composites

The insertion loss spectra of six different types of 10 mm thick composites are shown in Figure 9. At frequencies < 10 kHz, all the composites had insertion losses in the range 0 – 0.7 dB. At higher frequencies, the glass reinforced panels had higher insertion losses (in the range of 3 dB higher at 50 kHz) than the Spectra fibre reinforced panels. The effect of resin and weave is less clear from the data in Figure 9.

Statistical analysis of the data at 10 kHz and 40 kHz was carried out to determine if there were any significant effects of changing the fibre, resin, or weave on the insertion loss of the panels. The analysis indicated that the Spectra fiber panels had insertion losses that were lower than the glass panels at both frequencies. In addition, changing the resin from cyanate ester to epoxy, or the weave from 4H satin to 8H satin, had no statistically significant effect on the insertion loss.

The lower insertion loss of the Spectra fibre composites compared to the glass composites can be attributed to both density and sound speed. The density of the Spectra based panels (~ 1000 kg/m^3) is much closer to that of water (1000 kg/m^3) than the glass based panels (~1800 kg/m^3), and this accounts for much of the difference in acoustic behaviour for these two types of panels. The sound speeds of the Spectra reinforced panels are lower than the glass reinforced panels, and this contributes as well to the better performance of the Spectra panels.

Insertion Loss versus Panel Thickness

Plots of insertion loss versus frequency for 10 mm, 20 mm, and 30 mm thick glass/epoxy and Spectra/epoxy composites are shown in Figures 10 and 11 respectively.

There was a large increase in the insertion loss with thickness for the glass/epoxy panels at frequencies up to 20 kHz . At higher frequencies, thickness resonances dominate the insertion loss spectra, with peaks at frequencies corresponding to multiples of $\lambda/4$ and troughs at frequencies corresponding to multiples of $\lambda/2$. The insertion loss of the Spectra/epoxy panels is much less dependent on thickness than the glass/epoxy panels, as a comparison of Figures 10 and 11 demonstrates.

The acoustic material properties of the glass/epoxy and Spectra/epoxy composites, derived from insertion loss data were used to predict the dependence of acoustic behaviour on panel thickness. Figures 12 and 13 show plots of frequency against maximum thickness for insertion losses of 0.5 dB, 1.0 dB, 1.5 dB, and 2.0 for Spectra/epoxy and glass/epoxy composites respectively. For instance, if the frequency window of interest is 0 – 10 kHz and the insertion loss must be less than 1.5 dB, then the maximum thickness that may be used is 41 mm for Spectra/epoxy and 17 mm for glass/epoxy. Similarly, for a 0 – 30 kHz window and an insertion loss less than 1.0 dB, a Spectra/epoxy panel could be no thicker than 15 mm for and a glass/epoxy no thicker than 4 mm.

Stainless Steel Dome

A plot of insertion loss against frequency for a 1m x 1m section of a C5 sonar dome is shown in Figure 14 [9]. Above 10 kHz, the insertion loss is characterized by a series of resonance peaks and troughs resulting from the layered construction, and to a lesser extent, the internal steel ribbing. As can be seen from Figure 14, the insertion loss predicted for a steel/water/steel system with the same layer thicknesses as the dome agrees quite well with the experimental insertion loss.

An full scale stainless steel C5 dome was characterized at the DREA Barge in the Bedford Basin in 1998 [12]. Insertion loss measurements were carried out in the frequency range 10-100 kHz, with an acoustic projector outside of the dome and a receiving hydrophone inside the dome. The measurements were made at three different receiving positions inside the dome, and with many different bearing angles. Representative spectra from two measurements are shown in Figure 15. The insertion loss of the dome was found to be dependent on the location of the hydrophone and the angle of incidence of the projected sound.

Impacted Panels

Statistical analysis of the insertion loss data for the 10 mm thick Spectra or glass composites before and after impacts up to 236 J showed there was no significant effect of the impact damage on the measured insertion loss at 10 kHz or 40 kHz.

The effect of impact damage on the insertion loss of 20 mm and 30mm glass/epoxy and Spectra/epoxy composites (Table 4) was less clear than for the 10 mm panels. The panels were subjected to impact damage at Defence Research Establishment Atlantic, Dockyard Laboratory (Pacific) and the acoustic properties of the panels were determined after impact. The impact energies for these panels are summarized in Table 4. Note that the impact energy imparted to these panels increased with thickness. Figures 16 and 17 show plots of insertion loss against frequency for the Spectra/glass and epoxy/glass panels. None of the panels exhibited a significant increase in insertion loss at 10 kHz.

However, the 20 and 30 mm glass/epoxy panels and the 30 mm Spectra/epoxy panels were greatly affected by impact damage at higher frequencies. In fact, there was up to 8 dB increase in the insertion loss for the 30 mm Spectra/epoxy panel at 40 kHz as a result of impact damage.

The actual effect of an impact on the overall acoustic performance of a sonar dome constructed from a composite material will depend on the area affected by the impact in relation to the total area that is used as a window for sonar signals. For these experiments, the insonified area was generally larger than the impact damaged area. Based on an estimated 10 degree beamwidth of the parametric array source at a modulation frequency Fm = 20 kHz, the area insonified was approximately 14 cm in diameter. The area of the panels affected by the impact damage that could be assessed by visual means (ie strain whitening, cracking, plastic deformation) was approximately 8 cm in diameter.

Elastomer Coated Panels

The measured insertion of 10 mm undamaged glass/epoxy panels coated with 12.5 mm Isodamp C-1002 (EAR Corporation), 12.5 mm unfilled natural rubber, and 5 and 10 mm polyurethane are plotted against frequency in Figure 18. Most of the coatings resulted in a significant (> 2 dB) increase in the insertion loss, even at 10 kHz. The 12 dB insertion loss at 10 kHz measured for the natural rubber coated panel was surprising considering natural rubber has acoustic properties similar to water. An acrylic based pressure sensitive adhesive was used to join the elastomer to the glass/epoxy substrate. It is possible that air was trapped between the coating and substrate, and this would contribute significantly to the high insertion losses. It can be shown through modelling that even very thin layers of air can lead to very large insertion losses. For instance, a uniform 0.01 mm layer of air between the glass/epoxy panel and natural rubber coating is predicted to lead to an insertion loss of 11.5 dB, compared to 0.7 dB with no air gap present.

Figure 19 shows the insertion loss of the coated panels following impact. A decrease in the insertion loss was observed after the panels were subjected to impact damage. This decrease in insertion loss may be explained by an improved contact between the coatings and substrates as a result of impact loading. The panels were immersed in water for 24 hours prior to testing to ensure that no air bubbles would be present on the surface of the panel. An alternative explanation for the decrease in insertion loss is that air spaces in the interfacial region between coatings and substrates became filled with water prior to the second set of measurements.

The data suggests that the use of elastomeric coatings to mitigate impact damage of the sonar dome will require nearly perfect contact between the coating, adhesive, and substrate layers. Trapped air could be controlled (minimized) by applying appropriate loads during elastomer application, or by applying loads in a vacuum.

Self Noise Experiments

The intent of these experiments was to compare the acoustic radiation from mechanically excited composite panels with the radiation from the double walled stainless steel C5 dome material. It was anticipated that the composite materials, having higher material loss factors than stainless steel, would damp flexural vibrations in the panels to a greater extent than the steel panel, and therefore radiate less noise. The small scale experiments were not conclusive [9]. To evaluate self noise of dome materials, full scale tests should be carried out.

Angle Dependence of Insertion Loss

Measurements of 1 meter x 1 meter panels were made at 0, 30, and 60 degrees to normal incidence. The difference in the normal (0 degrees) and non-normal insertion loss data was panel and frequency dependent. The largest changes were observed for the glass reinforced panels at high frequencies. For example, the 10 mm glass/epoxy panel insertion loss at 40 kHz and normal incidence is 3.5 dB, versus 0.5 dB for the same panel at 60 degrees incident angle. For Spectra reinforced panels, the insertion loss was

generally in the range 0 to 1 dB for angles of incidence from 0 to 60 degrees, and frequencies 5 to 40 kHz.

Summary and Conclusions

The mechanical properties of the 8-H satin weave glass composites were superior to those for the 8-H satin weave Spectra fibre composites. The 8-H satin weave glass fabric composites were as much as 50% stiffer in tension and more than four times stronger when loaded in compression than the 8-H satin weave Spectra composites. They also exhibited as much as twice the in-plane stiffness and higher interlaminar shear than the Spectra composites.

The 8-H Spectra fabric composites were stiffer than the 4-H Spectra fabric composites under all loading conditions.

The resins had a slight effect on the mechanical properties of the composites. The higher modulus cyanate ester resin composites had somewhat better in-plane shear stiffness and showed a small improvement in compressive strength particularly for the 4-H Spectra fabric composites. The epoxy/4-H Spectra composite had higher interlaminar shear strength and higher tensile strength than the cyanate ester/4-H Spectra composite.

Under cyclic loading conditions, the glass composites failed in tension while the Spectra composites failed in compression. The Spectra composites exhibited hysteretic heating at moderately low testing frequencies and large permanent deformations prior to failure in fatigue tests. The Spectra composites crept under a mean sustained load.

At frequencies < 10 kHz, 10 mm composite panels as well as the stainless steel sonar window had insertion losses less than 1 dB. In terms of acoustic properties, there was no significant difference between panels incorporating the 8H and 4H satin weaves fabrics, or between the cyanate ester and epoxy resins. The reinforcing fibre had a much greater effect, with Spectra panels having lower insertion losses than glass panels under most conditions. This difference was small but statistically significant for thin (10 mm) panels

at low frequencies (< 10 kHz), but became much larger for thicker panels at higher frequencies.

Insertion loss data for the double walled stainless steel dome suggests that the current C5 window would not be suitable for higher frequency (>10 kHz) sonar applications. The high insertion loss of the stainless steel window, as well as peaks and troughs in its insertion loss spectrum at higher frequencies, would make target detection and classification difficult.

Small scale and full scale data suggest that if higher frequency capabilities of the sonar system are desired, then there would be definite advantages in using Spectra reinforced composite material for the dome. The insertion loss of 30 mm thick Spectra/epoxy panels is ~ 1 dB at 40 kHz, which is much lower than the 10 dB insertion loss for the stainless steel window at the same frequency. Calculations indicate that the detection range at 40 kHz of an active sonar system incorporating a Spectra fibre composite dome would be 8 times longer than the same system with a double walled stainless steel dome [11]. Since higher frequencies may be important for certain types of detection and tracking, the superior acoustic performance of Spectra composites should be considered in any upgrade to the present hull mounted sonar systems on Canadian frigates.

It may be that a composite sonar dome would have a greater effect on the performance of the sonar system through reduction in self noise than through lower insertion loss, especially at low frequency. This is supported by a previous study where it was reported that the C5 stainless steel window made a significant contribution to the sonar self noise [Reference 13, details classified]. The addition of free or constrained layer damping to the dome would be another approach to reducing dome self noise. Constrained layer damping is an integral aspect of the RHO-COR sonar dome material from BF Goodrich, which consists of a thick layer of rubber sandwiched between two glass reinforced plastic layers. Intrinsically damped composites are specifically designed to have high damping, and these types of materials should also be considered as potential dome materials.

The acoustic properties of Spectra and glass reinforced panels damaged by impacts were not greatly affected at low frequencies (< 10 kHz). However, at higher frequencies there was a significant increase in the insertion loss for 20 and 30 mm panels as a result of impact damage. The use of elastomeric coatings on the composite panels to mitigate impact damage is an approach that should be used with caution, since even small amounts of entrapped air can lead to large increases in the insertion loss.

In conclusion, Spectra fibre composites have superior acoustic properties to glass and carbon fibre composites and the double walled stainless steel material now used for the C5 sonar dome. The improvement in acoustic properties increases with frequency up to 100kHz. However, the mechanical properties of Spectra fibre composites are inferior to glass composites. Spectra fibre composites heat hysteretically under cycling loading, creep under sustained mean loads, and have poor properties in compression. Some of these drawbacks might be addressed by increasing the thickness of a spectra fibre composite dome, but this would increase costs and decrease acoustic performance.

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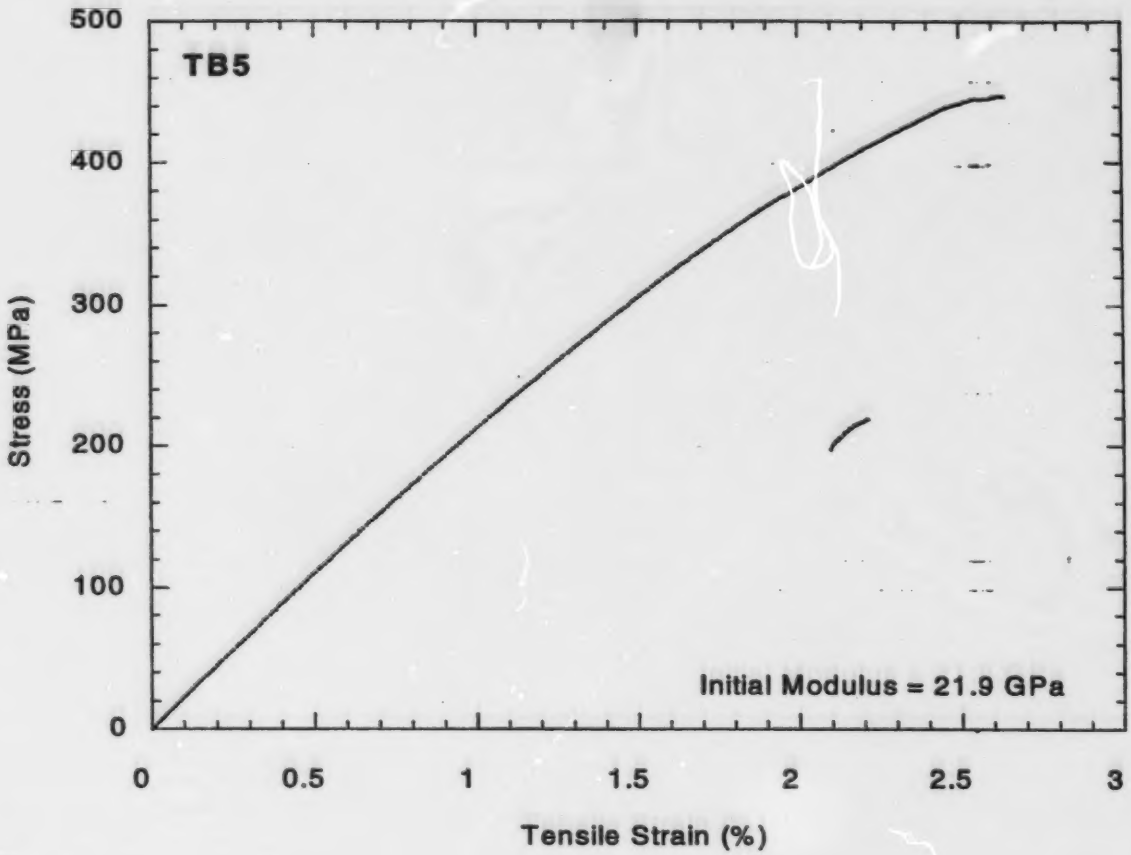

Figure 1 – Typical stress strain plot for glass/cyanate ester composite. Although the compression half of the stress strain plot is not shown, the compression and tensile moduli were the same for the glass composites.

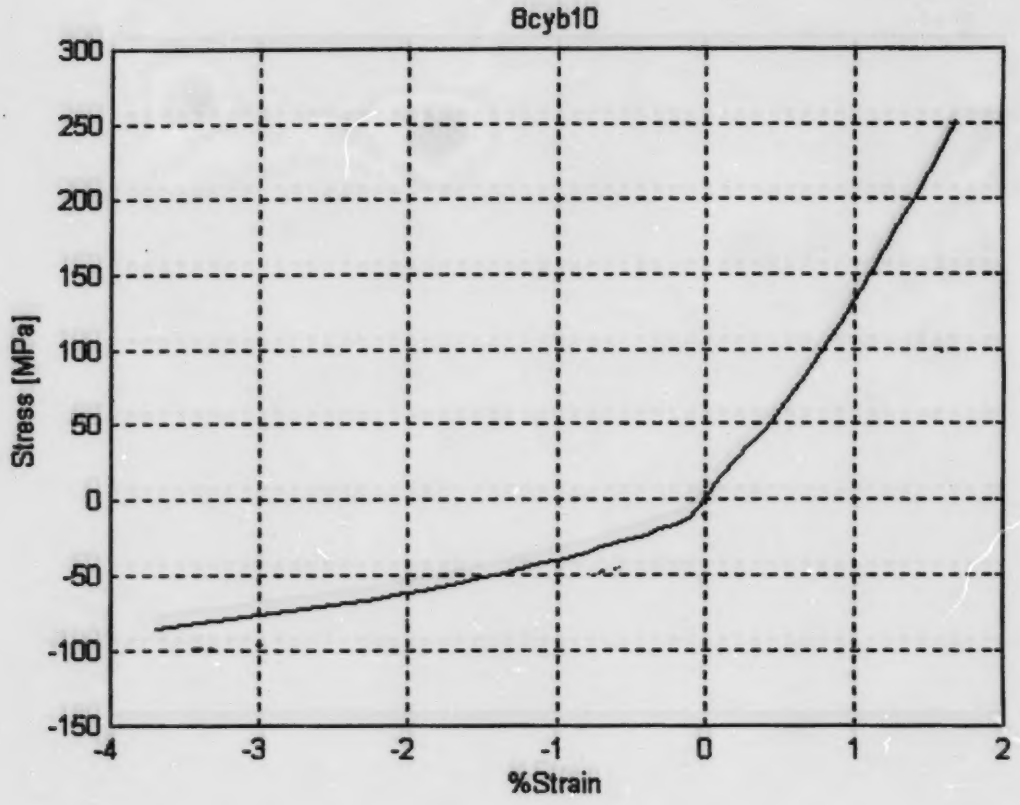

Figure 2 – Typical stress strain plot for a Spectra fibre/cyanate ester composite.

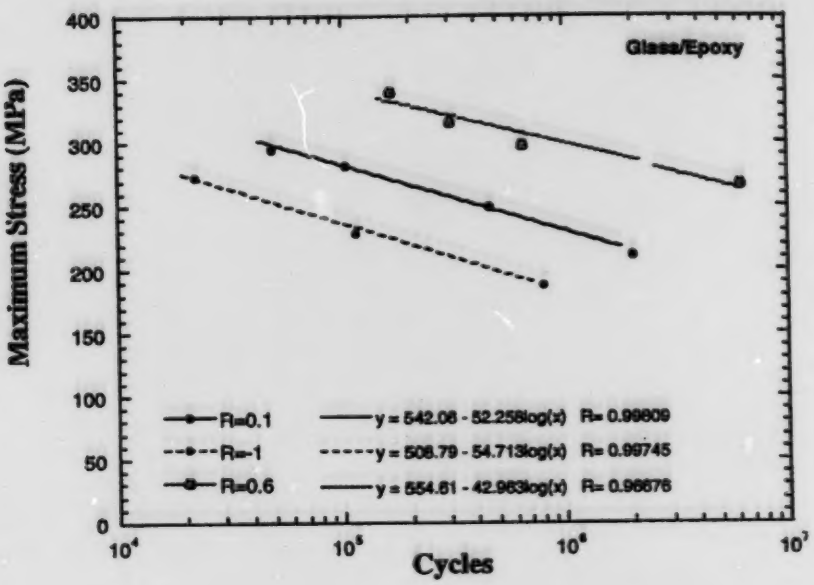

Figure 3 – Effect of R ratio on the fatigue life of a glass/epoxy composite.

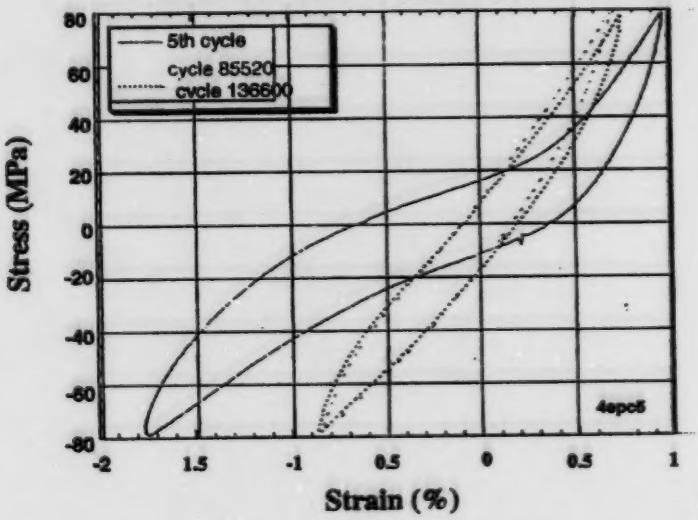

Figure 4 – Stress strain curve for Spectra/epoxy composite in four point bend fatigue test (R = -1).

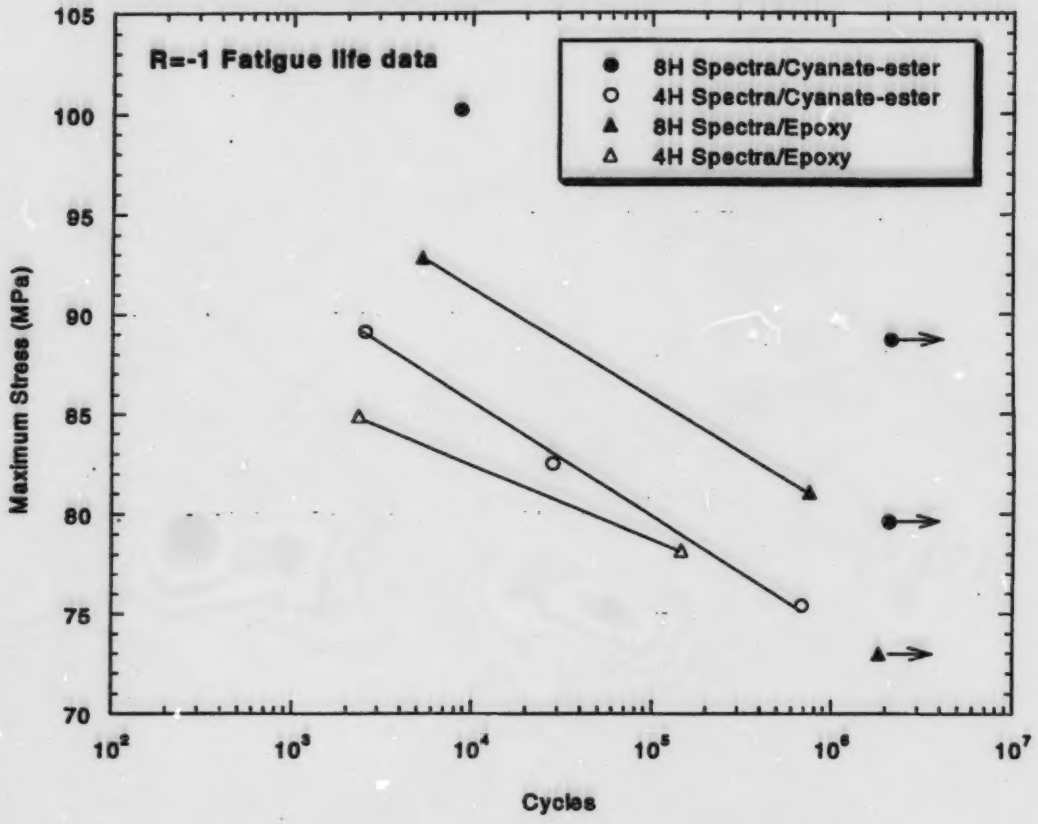

Figure 5 – Results of fatigue testing of Spectra fibre composites in the reverse bending mode.

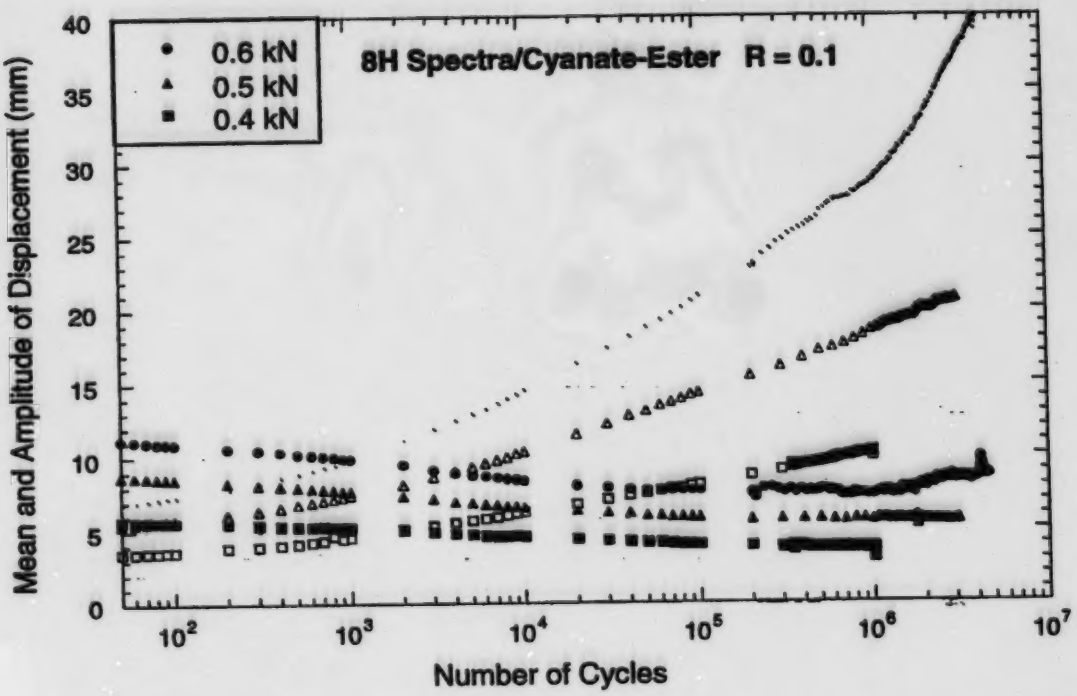

Figure 6 – Plot of displacement amplitude required to maintain a constant load for a Spectra/cyanate ester composite.

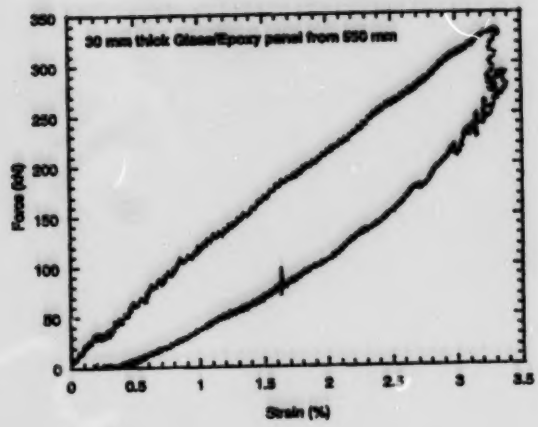

Figure 7 – Force-strain plot for 20 mm thick glass/epoxy composite.

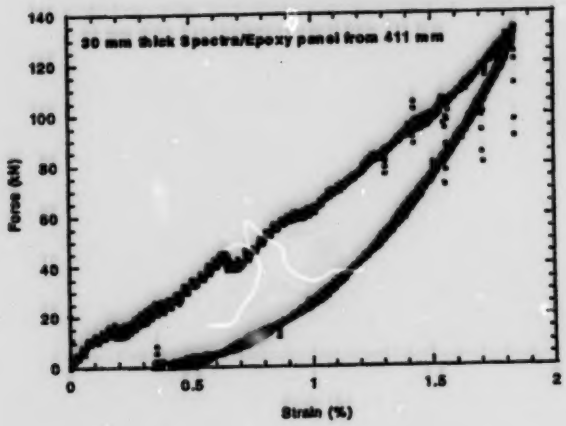

Figure 8 – Force-strain plot for a 30mm thick Spectra/epoxy composite.

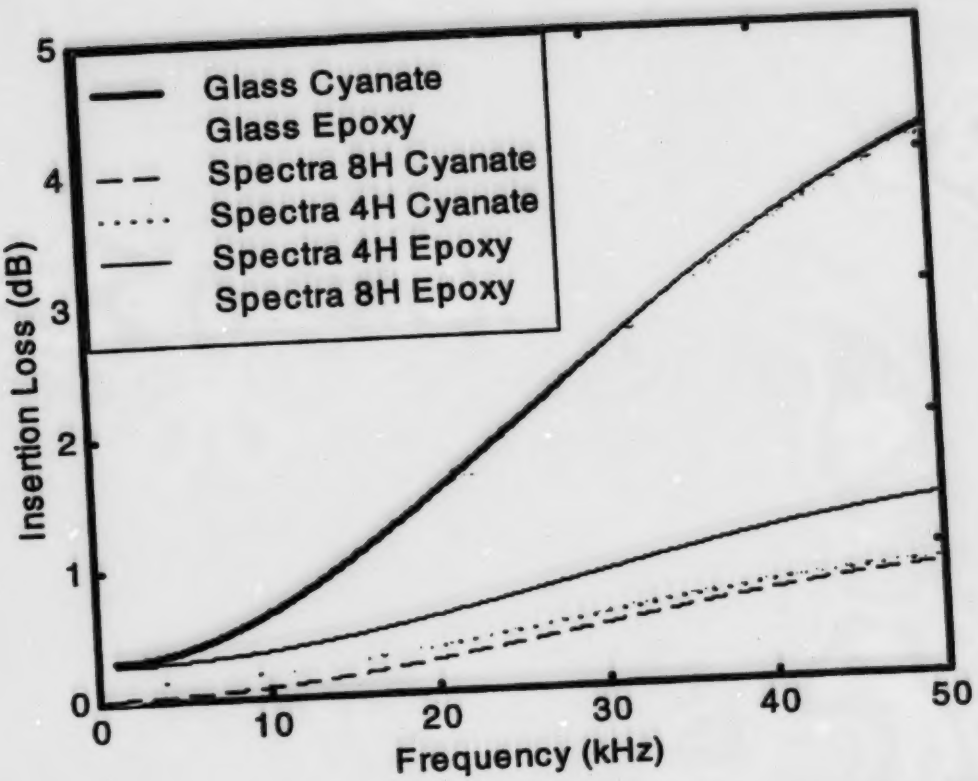

Figure 9 - Insertion loss of undamaged 10 mm thick composite panels calculated using known thickness and density, and optimized sound speed (c) and α. Calculated using Method B in Reference 11.

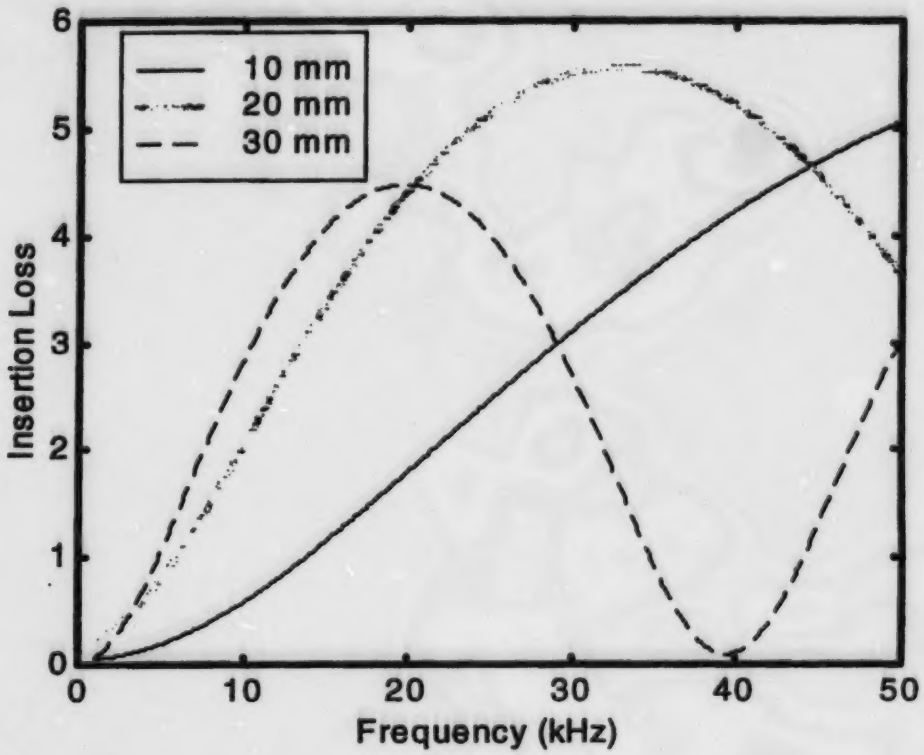

Figure 10 - Insertion loss of glass/epoxy panels for three different thicknesses calculated using known thickness and density, and optimized sound speed (c) and α. Calculated using Method B in Reference 11.

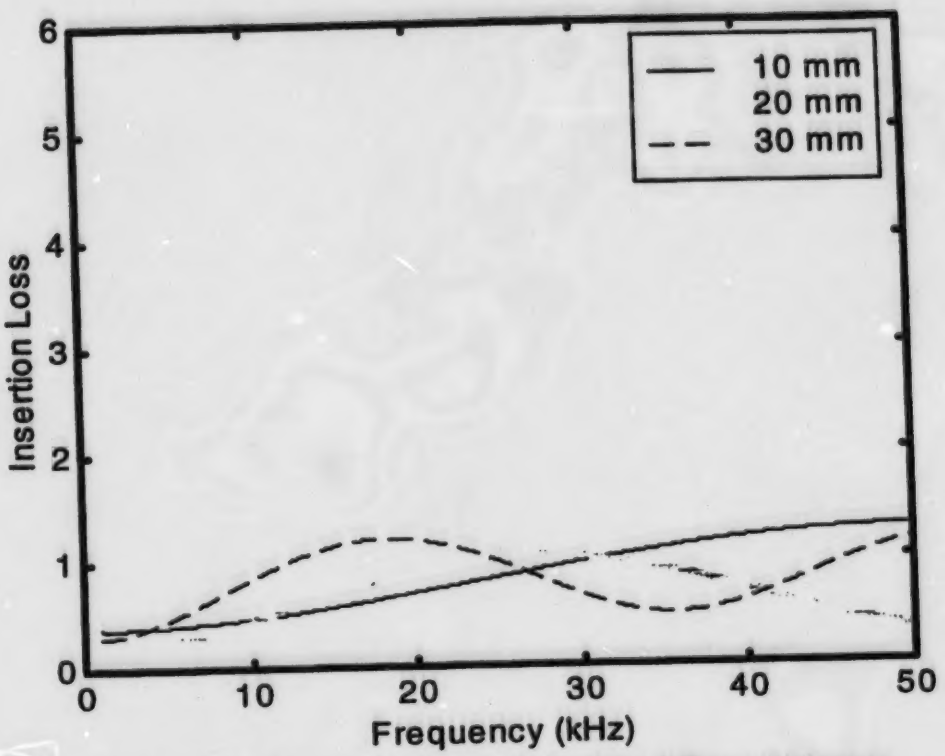

Figure 11 - Insertion loss of Spectra/epoxy panels for three different thicknesses calculated using known thickness and density, and optimized sound speed (c) and α. Calculated using Method B in Reference 11.

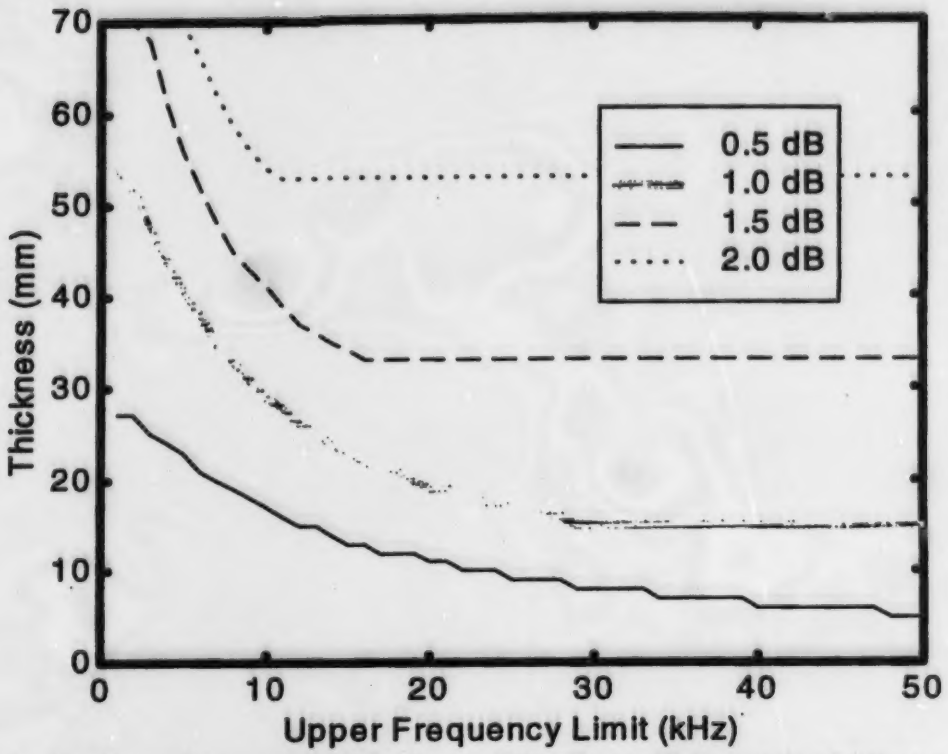

Figure 12 - Upper frequency limit for the condition IL < x dB for panels of different thickness, calculated using the following material properties for Spectra/epoxy composites: $\rho = 1009$ kg/ m^3, $c = 2190$ m/s, $\alpha = 3.07$ Np/ m.

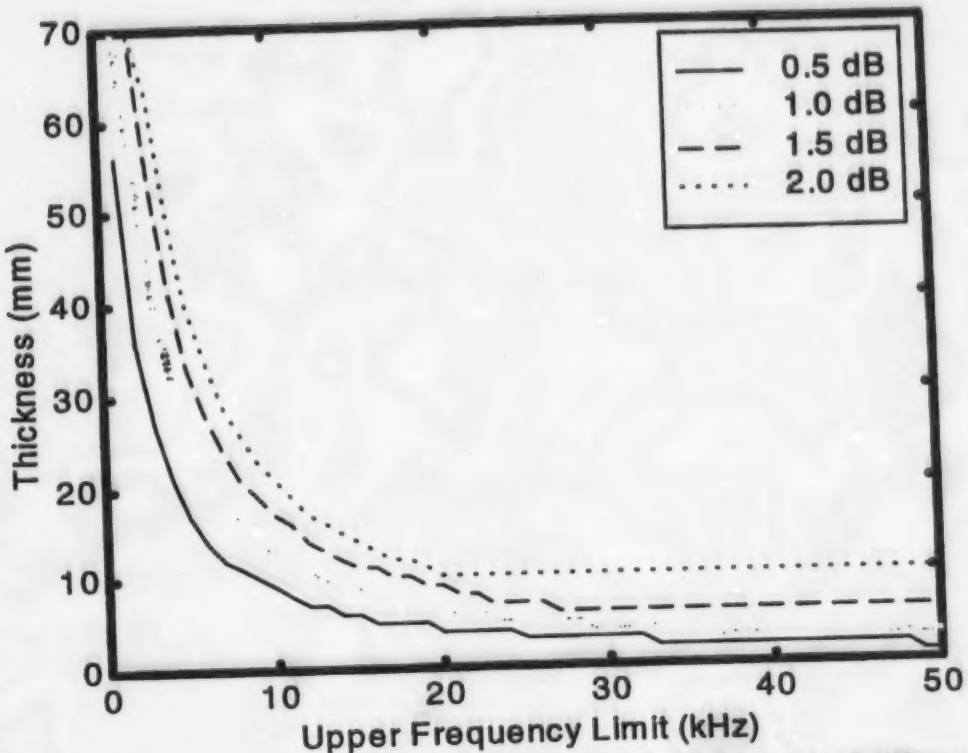

Figure 13 - Upper frequency limit for the condition IL < x dB for panels of different thickness, calculated using the following material properties for glass/epoxy composites: $\rho = 1840$ kg/ m^3, $c = 2720$ m/s, $\alpha = 2.07$ Np/ m.

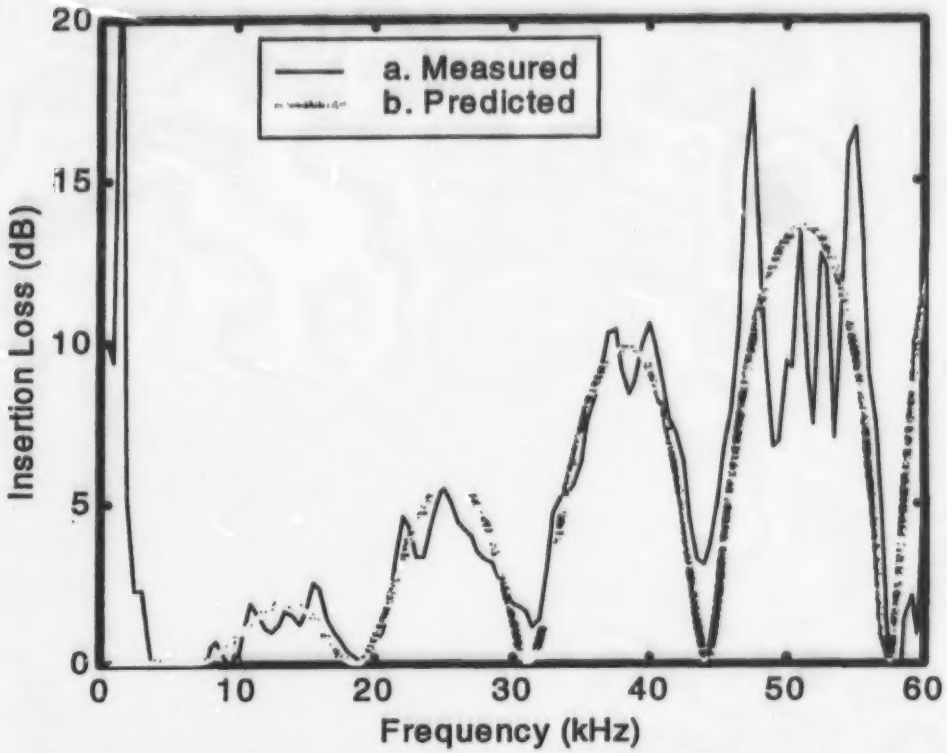

Figure 14 - Normal incidence insertion loss of C5 double walled stainless steel dome. (a) Experimental data from 1 meter x 1 meter section [9] and (b) predicted insertion loss for 1.57 mm steel/54 mm water/1.57 mm steel calculated using methods described in S.M. Whelan, V.H. Chin, and J. Guigné, "A Multilayered Model for Simulation of Acoustical Parameters", DREA Contract Report CR/93/408.

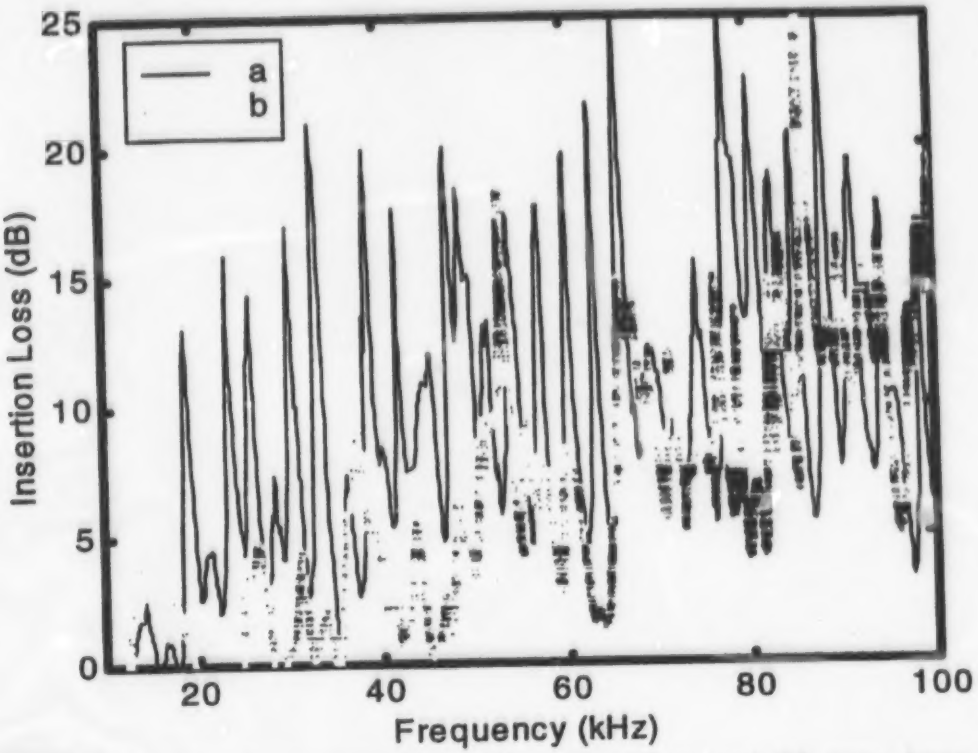

Figure 15 - Insertion loss spectra of a full scale stainless steel C5 sonar dome from experiments at the DREA Barge. (a) Receiving hydrophone located in lower part of dome. Projector located 15 degrees down from hydrophone position, and at a bearing of 20 degrees from the main axis of the dome. (b) Receiving hydrophone located in upper part of dome. Projector at same depth as hydrophone, and at a bearing of 20 degrees from the main axis of the dome. Reproduced with permission from Ian Cobb, FMF Cape Scott, Halifax, Nova Scotia.

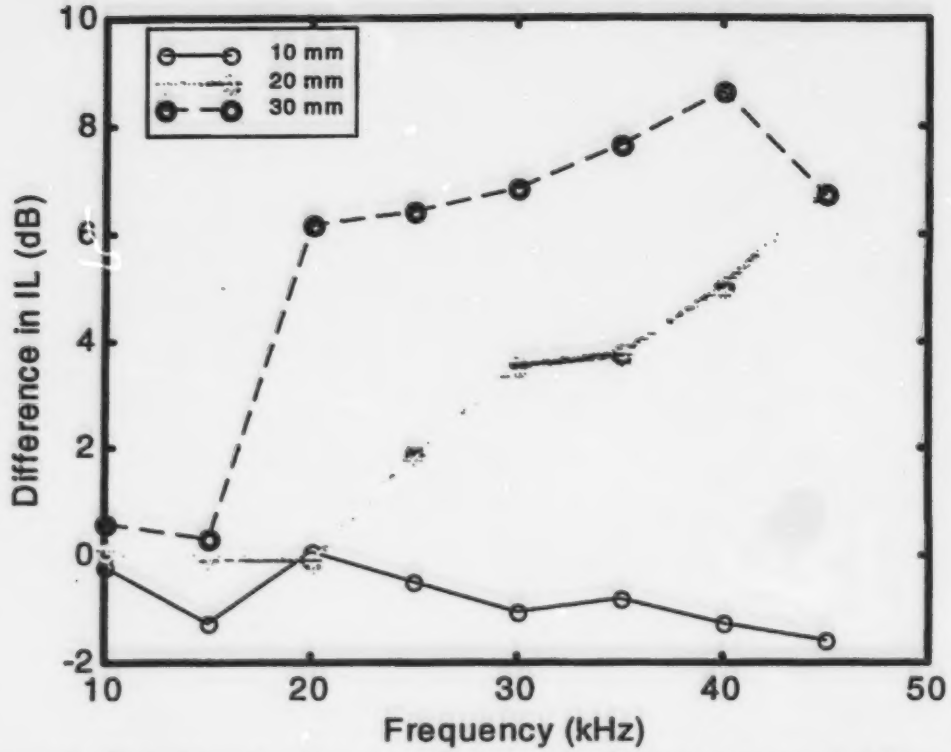

Figure 16 – Plot of insertion loss versus frequency for Spectra/epoxy panels following impact damage. Insertion loss was computed using Method A in reference 11.

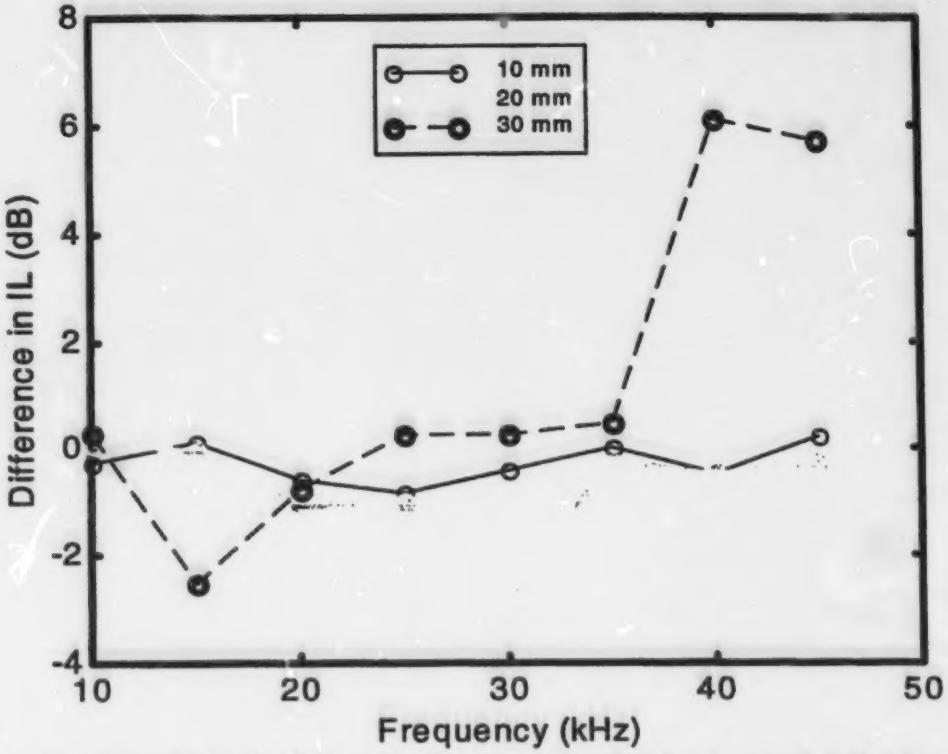

Figure 17 – Plot of insertion loss versus frequency for glass/epoxy panels following impact damage. Insertion loss was computed using Method A in reference 11.

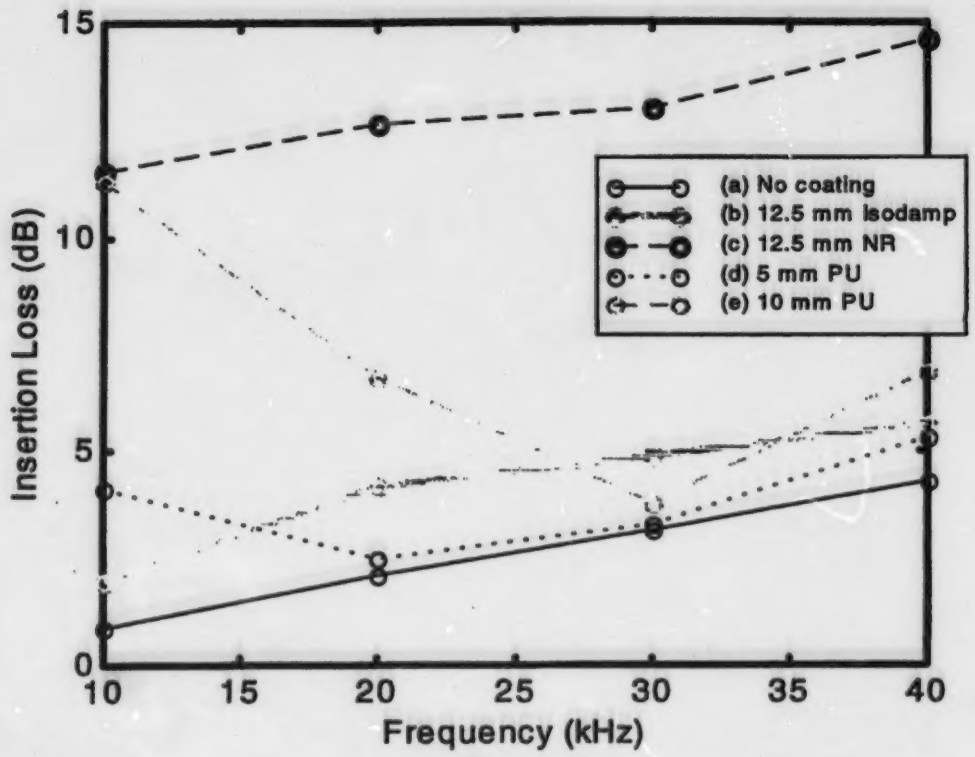

Figure 18 - Plot of insertion loss versus frequency for undamaged 10 mm glass/epoxy panels: (a) uncoated panel, (b) 12.5 mm EAR Isodamp C-1002, (c) 12.5 mm natural rubber, (d) 5 mm polyurethane, (e) 10 mm polyurethane. Insertion loss was computed using Method A in reference 11.

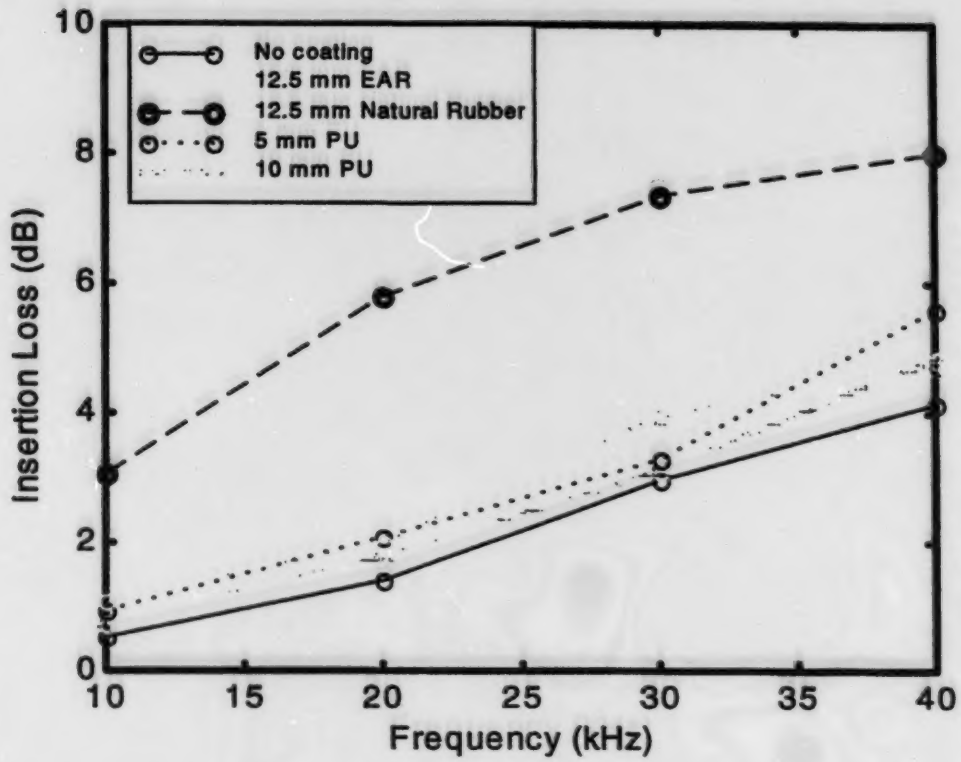

Figure 19 - Plot of insertion loss versus frequency for 10 mm glass/epoxy panels following impact damage: (a) uncoated panel, (b) 12.5 mm EAR Isodamp C-1002, (c) 12.5 mm natural rubber, (d) 5 mm polyurethane, (e) 10 mm polyurethane. Insertion loss was computed using Method A in reference 11.

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This report summarizes research carried out under a DMCS 3 (DMSS 7) tasking entitled "Comparison of the Acoustic, Self Noise, and Mechanical Properties of Composite and Stainless Steel Sonar Dome Materials". It incorporates results from several contracted research programs and DREA Technical Memoranda and is meant to provide a concise record of the tasked research. Static (tensile and compression tests), fatigue and impact testing were used to characterize the mechanical properties of high strength polyethylene (Spectra) and glass fibre composites. Insertion loss measurements were used to characterize the acoustic performance of the composites. The effect of impact damage and angle of incidence of sound on the performance of the composites were also measured. The results show that Spectra fibre composites have superior acoustic properties compared to glass fibre composites and the double walled stainless steel presently used in the C5 sonar dome. However, the mechanical properties of the Spectra composites were inferior to the glass composites.

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Spectra fibre
Epoxy
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Fatigue
Impact
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